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"ON THE INTERACTION BETWEEN DAMAGE AND MOISTURE SORPTION IN CROSS-PLY LAMINATED COMPOSITES"

By

Kh. Abdel-Tawab and Y. Weitsman

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ON THE INTERACTION BETWEEN DAMAGE AND MOISTURE SORPTION IN CROSS-PLY LAMINATED COMPOSITES

Khaled Abdel-Tawab and Y. Jack Weitsman

Department of Mechanical and Aerospace Engineering and Engineering Science

The University of Tennessee, Knoxville, TN 37996

ABSTRACT: The interaction between moisture sorption and damage in the form of transverse cracks in cross-ply laminated composites is studied assuming a linear Fikian diffusion process. Finite element computational results, which account for the two-dimensionality of the problem and anisotropy of the laminae, are compared against analytical predictions of one-dimensional diffusion. It is shown that, for the lay-up under consideration, the effect of transverse cracks on total moisture weight-gain becomes noticeable only when the crack density approaches the characteristic damage state (CDS).

INTRODUCTION

Laminated composites are increasingly used in engineering applications that involve exposures to ambient humidities. Therefore, for a reliable and economic design of structures made of laminated composites, it is necessary to study moisture sorption in these materials and the consequent effects on mechanical behavior.

Under service conditions, laminated composites may also undergo damage in the form of microcracks, which can affect the sorption process and hence the moisture weight-gain measurements. The objective of this article is to provide some guidelines for both experimental and analytical investigations of moisture content in transversely cracked cross-ply laminated composites.

The effect of microcrack damage on the sorption process was investigated recently [1] for tubular angle-ply laminated composites intended for use in the piping industry. In that study, damage was associated with the reduction in axial stiffness, but was

not physically observed. The main experimental finding was that microcrack damage prompted a faster water absorption by the material but retained the essential form of the absorption (diffusion) law of the uncracked material. To account for this, the influence of damage was incorporated within an "effective time" that governed the diffusion process. Using the concept of effective time, both Fickian and a two-phase diffusion [2] models were used to fit the experimental data for the moisture content.

In the present article, the effect of transverse cracks in the 90° ply group on moisture content in cross-ply laminated composites is investigated by considering moisture sorption to occur across the transverse crack surfaces as well as the top and bottom laminate surfaces. Hence the sorption process is two-dimensional. The present analysis also accounts for the anisotropy of laminated composites. For simplicity, we consider a diffusion process governed by Fick's law.

FORMULATION

Consider a transversely cracked $[0_{\mathrm{m}}/90_{\mathrm{n}}]_{\mathrm{s}}$ cross-ply laminate as shown in Figure 1. It is assumed that the transverse cracks are uniformly spaced at distance L from each other. The damage variable is chosen as the transverse crack density ω which is defined [3] as the ratio between the thickness of the 90° ply group and the crack spacing; namely

$$\omega = \frac{2\,h_{90}}{L}\,. \tag{1}$$

Each ply group is assumed to be transversely isotropic. Thus, for two-dimensional diffusion in the x_1x_2-plane, Fick's law in each 0° ply group takes the form [4]

$$J_1 = -D_L\,\frac{\partial c}{\partial x_1} \quad , \quad J_2 = -D_T\,\frac{\partial c}{\partial x_2}\,, \tag{2}$$

and in the 90° ply group it takes the form

$$J_1 = -D_T\,\frac{\partial c}{\partial x_1} \quad , \quad J_2 = -D_T\,\frac{\partial c}{\partial x_2}\,, \tag{3}$$

where J_1 and J_2 are components of the moisture flux vector in the x_1 and x_2 directions, respectively; c is the moisture concentration; and D_L and D_T are the diffusion coefficients in the longitudinal (parallel to the fibers) and transverse (normal to the fibers) directions, respectively.

The diffusion coefficients D_L and D_T can be determined from the diffusion coefficient of the matrix D_m and that of the fibers D_f using homogeneization techniques. Since D_f is typically very small compared to D_m the following approximation can be used for a fiber volume fraction $V_f < 0.785$ [5]

$$D_L = (1 - V_f)\, D_m \,, \tag{4}$$

and

$$D_T = (1 - 2\sqrt{V_f \,/\, \pi})\, D_m \,. \tag{5}$$

We introduce the degree of anisotropy γ as the ratio between D_L and D_T

$$\gamma = \frac{D_L}{D_T} = \frac{1 - V_f}{1 - 2\sqrt{V_f \,/\, \pi}} \,. \tag{6}$$

It is clear that γ increases with V_f, and the lower limit $\gamma = 1$ (at $V_f = 0$) corresponds to an isotropic response.

Due to the complex geometry and material anisotropy, the finite element method is used to perform the analysis. In view of symmetry of the problem it suffices to consider only one quarter of the domain between any two adjacent cracks as shown in Figure 2. It is assumed that the transverse cracks are subjected to the same constant moisture concentration boundary condition ($c = c_o$) as the laminate surfaces. The boundary conditions along with the proper symmerty conditions are shown in Figure 2.

It should be noted that the moisture concentration c remains finite at the transverse crack tip at all times. This follows from the analogy between the present problem and that of heat conduction governed by Fourier's law [6] where it was found that the temperature remains finite at the crack tip.

The analysis was performed using the ABAQUS finite element program supplemented with a post-processing subroutine that integrates the moisture concentration c to obtain the total moisture content M

$$M(t) = \int_0^h \int_0^{L/2} c\,(x_1, x_2, t) \;\; dx_1\, dx_2 \,, \tag{7}$$

where $h = h_0 + h_{90}$ is half the laminate thickness. In the analysis both the transverse crack density and the degree of anisotropy were varied by considering different values of ω and γ, respectively.

RESULTS AND DISCUSSION

From the finite element analysis it was found that varying the degree of anisotropy γ in the range corresponding to $0 \leq V_f < 0.785$ has an insignificant effect on the total moisture content. For all values of the transverse crack density ω considered (Figure 3) a maximum difference of less than 3% in the moisture content is encountered over the entire range of γ. Thus, in the remaining part of the analysis the anisotropy is neglected and the response is considered to be isotropic with a common diffusion coefficient D_T.

Different values for the transverse crack density ω were utilized in the finite element runs and results corresponding to three of these values are shown in Figure 3. The results in that figure are presented in terms of a non-dimensional time t^* given by

$$t^* = \frac{t\,D_T}{h^2}\,, \tag{8}$$

where t is the actual time. Also, the transient moisture content M is normalized by the steady-state (maximum) moisture content $M(\infty) = c_o\,h\,L\,/\,2$. For comparison purposes, the analytical solution for one-dimensional diffusion [4] across the laminate surfaces only (i.e. in the absence of transverse cracks) is also shown in Figure 3.

From Figure 3a it is clear that for small values of ω the effect of the transverse cracks on moisture content is negligible. For intermediate values of ω (Figure 3b) the effect is more pronounced, but still falls within the typical scatter band of weight-gain data collected under one-dimensional diffusion. Figure 3c corresponds to a limiting crack spacing of $L = 2\,h_{90}$, which approximates the so-called " characteristic damage state" (CDS) of the laminate [7]. In this case, the effect of the transverse cracks is quite considerable and can be readily detected in an experimental program.

Following common practice in continuum damage mechanics, damage can also be measured through the reduction in stiffness. The damage variable can then be expressed as [8]

$$\omega' = 1 - \frac{\bar{E}_1}{\bar{E}_1^{\circ}}\,, \tag{9}$$

where $\bar{E}_1$ is the overall damaged axial modulus and $\bar{E}_1^{\circ}$ is the overall virgin axial modulus; both moduli measured in the x_1–direction. Suri and Perreux [1] adopted expression (9) as a measure for damage, and investigated moisture sorption for different

values of ω' up to 0.33. For transversely cracked cross-ply laminates, the ratio $\bar{E}_1 / \bar{E}_1^{\circ}$ can be determined using a shear lag analysis [3]. Using material properties for an AS4/3501-6 $[0/90_3]_s$ graphite/epoxy laminate [3], it is found that the cases considered in Figure 3a, b, and c correspond to $\omega' \approx 0.06, 0.08$, and 0.17, respectively. Larger values for ω' can be realized by considering other cross-ply laminates having larger h_{90} / h_0 ratios.

It is clear that large variations in the transverse crack spacing correspond only to small variations in stiffness reduction. The latter become even smaller for smaller values of the ratio h_{90} / h_0. For cross-ply laminates, it is thus clear that expression (1) is more appropriate and informative than (9), at least in accounting for variations in the transverse crack spacing. On the other hand, for angle-ply laminates and other complex laminate lay-ups undergoing distributed damage, direct observations of the cracks are more difficult to perform and expression (9) could be easier to adopt as a damage measure.

It should be noted that the idea of incorporating damage into "effective time" [1], does not seem to be suitable for diffusion in cross-ply laminates due to two reasons. Firstly, the presence of the transverse cracks renders the sorption process to be two-dimensional. Generally, a transient two-dimensional boundary value problem cannot be reduced to a transient one-dimensional problem with an effective time. Secondly, for the concept of "effective time" to be meaningful, a horizontal shift function of damage should exist such that the moisture content curves corresponding to different levels of damage can be collapsed onto one master curve. This is similar to the well-known time-temperature shift function used to coalesce creep curves at different temperatures onto one master creep curve [e.g. 9]. From Figure 3, it can be observed that such a shift function does not exist except possibly during the early stages of diffusion when M is linearly proportional to $\sqrt{t^*}$. However, the concept of effective time may be useful for diffusion in more complex laminate lay-ups.

Finally, it should be noted that sorption tests are typically performed in two circumstances; either under exposure to humid air or with the specimens completely immersed in fluids. In the latter circumstance, if the cracks are not drained, the weight of the

liquid entrapped in the cracks would contribute to the measured weight-gain. The present analysis does not account for such weight-gain and hence can be considered to replicate moisture content data for tests performed in humid air. In immersed environments the results presented herein remain valid provided that complete drainage of the cracks is allowed prior to weight-gain measurements, a process that may take only a few minutes to complete in typical test coupons.

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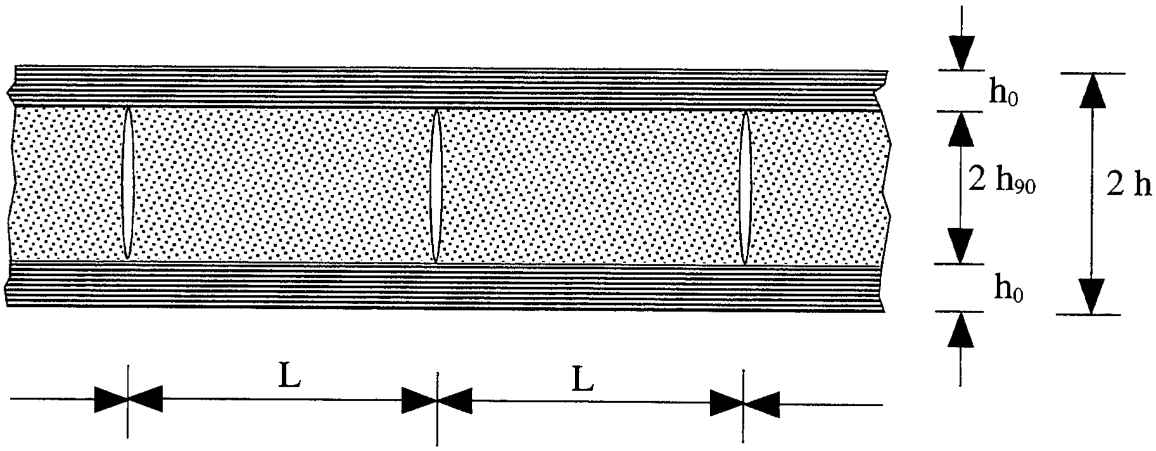

Figure 1. The transversely cracked crossply laminate considered in the analysis.

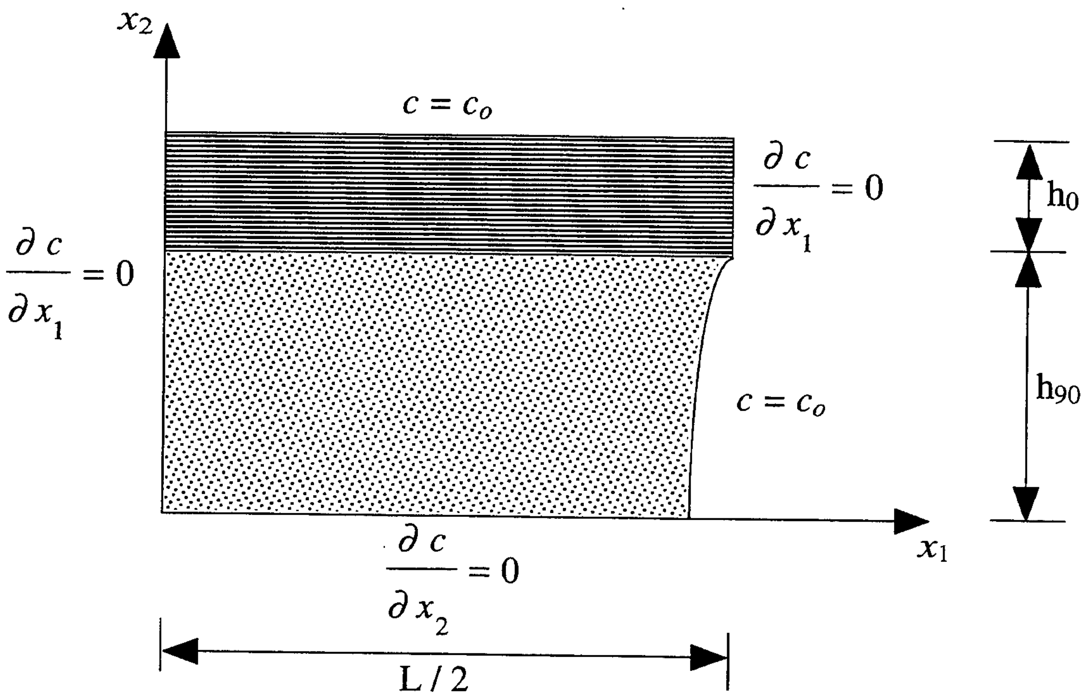

Figure 2. Geometry and the boundary and symmetry conditions considered in the finite element analysis.

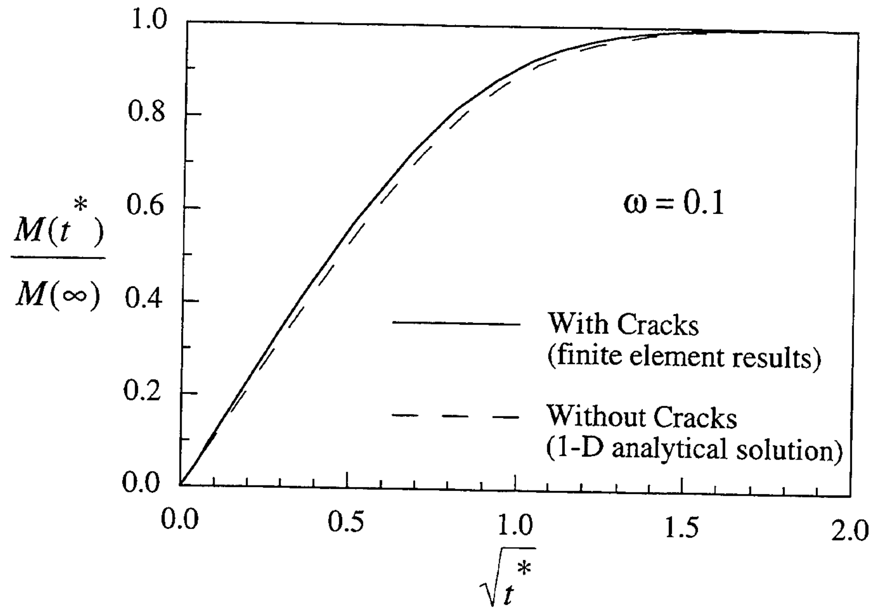

Figure 3a

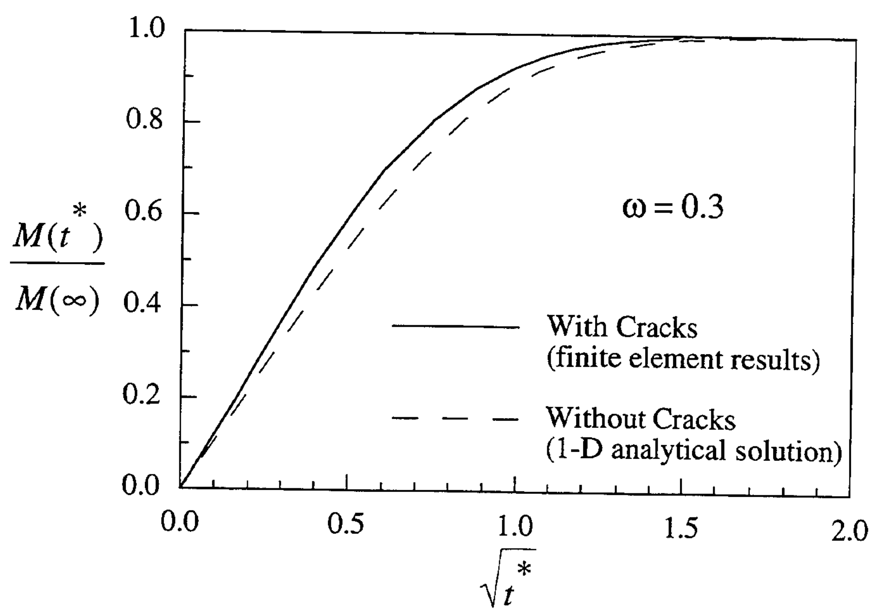

Figure 3b

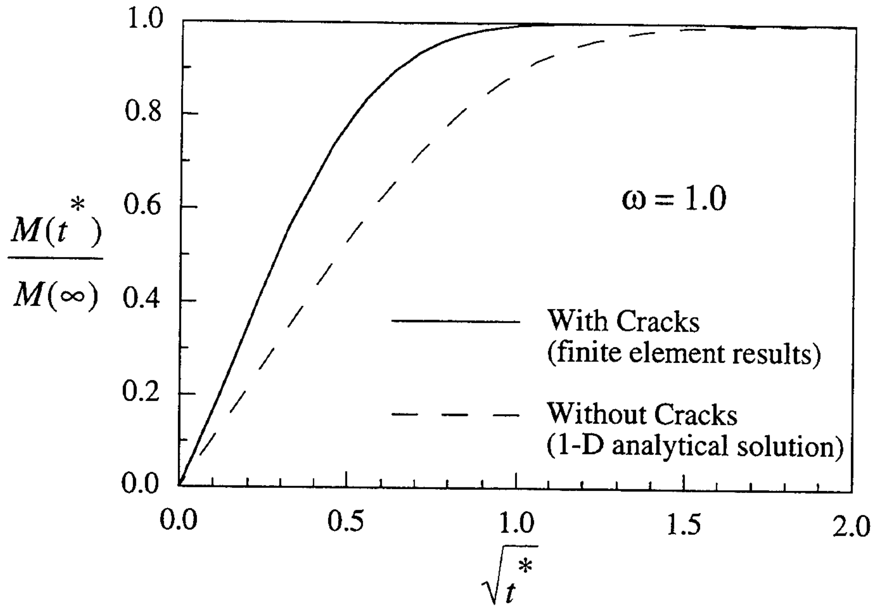

Figure 3c

Figure 3. Normalized moisture content as a function of non-dimensional time for different values of transverse crack density ω $(\omega = 2h_{90}/L)$.